

CRASH ATTRIBUTES THAT INFLUENCE THE SEVERITY OF ROLLOVER CRASHES

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ABSTRACT

This paper examines NASS/CDS 1995 to 2001 in order to evaluate rollover crash severity metrics and to recommend additional data elements to assist in determining rollover severity.

For belted occupants and unbelted ejected occupants in single vehicle crashes, the number of roof impacts is an appropriate severity indicator. For ejected occupants, the ejection risk generally increases with the number of quarter-turns. However, number of roof impacts provides a more uniform relationship between crash severity and injury risk.

For the population of crashes with another vehicle prior to rollover, the injury risks are higher than for single vehicle crashes. Impacts with a fixed object such as a tree or wall prior to rollover also carry higher injury risks. Consequently, additional severity measures such as the delta-V for the pre-rollover crash event are required in addition to the rollover severity measures.

For non-ejected unbelted occupants in single vehicle crashes, the most frequent and most injurious category was one quarter-turn. An examination of cases with one quarter-turn showed that the majority of the injuries were in rollovers that were stopped by impacts with trees and poles. In most of these cases, the point of impact was the roof. Additional data elements to permit easy identification of rollover cases that also involve planar crashes with fixed objects during the rollover would be desirable. Crash severity metrics associated with planar crashes may be applicable to these cases.

INTRODUCTION

Rollover crashes continue to be a growing source of motor vehicle injuries and deaths in the United States. One of the difficulties in analyzing rollover crashes and designing countermeasures is the lack of a standard measure of crash severity. Rollover severity factors equivalent to delta-V, used in planar crashes, are not currently available in the crash data files. A number of factors are currently recorded that might be related to crash severity. These include: pre-crash speed (estimate), number of quarter-turns of roll, extent of vehicle damage, single or multi-vehicle event, and rollover initiation type. In earlier studies of accident data, Malliaris found that pre-crash velocity was the most influential rollover crash severity parameter [Malliaris, 1991]. In a companion paper, Digges applied computer modeling to rollover crashes and found that increases in vehicle rotation rate and vertical velocity also increased rollover severity [Digges, 1991]. None of these suggested parameters (pre-crash velocity, vertical velocity, and rotation rate) are readily available from after-the-fact crash investigations. However, in the future, on-board crash recorders may make it practical to collect these added parameters in real time and store the results.

The purpose of this paper is to analyze recent NASS/CDS rollover crashes to determine rollover crash severity variables that can be measured or computed using currently available crash investigation methods. The suitability of attributes that can be based on data elements currently documented in NASS/CDS is the primary focus of this analysis.

Crash severity is an important factor in calculating the benefits of a countermeasure. It is desirable to have a crash severity measurement that can be related to the rate of injury. When a safety feature is introduced that reduces the risk of injury for a range of crash severities, the injury reduction for a fleet of vehicles can be calculated. For the analysis to follow, the recommended crash severity parameters are those that predict increasing injury rate with increasing crash severity. The injury rate is measured

in terms of the number of serious and fatal injuries per 100 occupants in the exposed population.

The rollover crash is complicated by a number of confounding factors. Ejection is an intermediate outcome that increases the risk of fatality by a factor of more than 5 [Malliaris, 1987]. By paired comparison analysis of FARS data, Malliaris showed that the fatality reduction effectiveness of ejection avoidance was around 70% [Malliaris, 1987]. Kahane found that “two-thirds of the fatalities in rollovers involve occupants being ejected from the car, often in crashes with low damage” [Kahane 1989]. Deutermann confirmed Kahane’s findings, reporting that in 2000, 62 percent of those occupants killed in fatal rollovers were ejected [Deutermann, 2002]. It is evident that ejection is an undesirable outcome of a rollover. A crash severity parameter that predicts increasing rate of ejection is considered to be as valid as one that predicts the risk of severe injury.

In some cases, the rollover follows a planar crash. The planar crash may be with another vehicle or with a fixed object. In these planar impact crashes, the initial impact may have contributed to the injury. Consequently, crash severity metrics associated with planar crashes in addition to the rollover crash may apply. Countermeasures that are applicable to preventing ejection may not be applicable to preventing injury in the planar crash. The crash severity metric for these combined planar and rollover crashes should be different from those in which ejection is the primary risk factor. The rollover/planar class of crashes would need to be identified by an added data element in the recorded data.

The data element in NASS that is most easily related to rollover severity is the number of quarter-turns that the vehicle rotates during the rollover. The number of quarter-turns is generally related to the energy of the crash. However, confounding factors, such as, vehicle geometry, vehicle deformation, and subsequent impacts can modify the number of quarter-turns. If the rollover is abruptly stopped by an impact with a fixed object such as a tree or a wall, the resulting injury may be caused by the planar impact. As in the case of the pre-rollover impacts, planar crash severity metrics may apply to this class of rollover, as well.

DATA SOURCE

The data source for this paper is NASS/CDS years 1995-2001. The NASS/CDS is a national sample of

crashes in the United States. A condition for entry in the database is that one light vehicle must be damaged sufficiently that it is towed from the crash scene. For the 1995-2001 time period, the database contains 25,179 crashes that involve 38,118 vehicles and 54,311 occupants. Each NASS case is assigned a weighting factor that permits the data to be extrapolated to predict national averages. Unless otherwise noted, the information presented in this paper is based on weighted data.

Until 1995, NASS/CDS documented the number of quarter-turns in four categories – 1, 2, 3, and 4+. There was also a category for end over end rollovers. Since 1995, NASS/CDS has documented up to 16 quarter-turns. Greater numbers of quarter-turns are designated in this paper as 16+. This additional resolution allows a better evaluation of the number of roof impacts as well as the number of quarter-turns.

In addition, NASS/CDS has classified the cause that initiated the rollover. There are ten categories of initiation, one of which is collision with another vehicle. The other categories are: Trip-over, Flip-over; Turn-over, Climb-over, Fall-over, Bounce-over, Other, End-over-end, and Unknown. Some of the categories may involve injury producing impacts with fixed objects before the rollover. The category, collision with another vehicle, frequently involves an injury producing vehicle-to-vehicle crash prior to the rollover. In cases involving pre-rollover impacts, crash severity measures other than those normally assigned to rollovers may be required. The analysis to follow will be subdivided into single vehicle crashes and multi-vehicle crashes. The single vehicle crashes will include all known initiation categories except multi-vehicle.

In this study of crash severity, only the front seat occupants ages 12 and older are included. This was done to reduce the bias of occupancy rate on the resulting crash severity.

The combined years 1995 to 2001 contain records of 3,871 vehicles that were involved in rollover crashes. These vehicles had 5,227 front seat occupants, age 12 years and older. This population sustained 1,309 MAIS 3+ and fatal injuries. When the NASS weighting factors are applied, these cases are expanded to 1,484,669 vehicles and 1,946,677 front seat occupants age 12 and older with 125,768 MAIS 3+ and fatal injuries.

EXPOSURE AND INJURIES BY VEHICLE CLASS

The distribution by vehicle type of front seat occupants aged 12 and older and front seat occupants aged 12 and older with serious and fatal injuries in rollover crashes is shown in Table 1. Occupants with serious and fatal injuries are classified as “MAIS 3+ F”. This category includes all survivors with MAIS 3 or greater injury, and all fatally injured regardless of their MAIS injury level. The table also shows the rate of MAIS 3+ F injured to front seat occupants per 100 exposed to rollover crashes. This ratio is referred to as injury rate in Table 1 and in the Tables to follow. This ratio is an indicator of the severity of a population of crashes with regard to their ability to produce MAIS 3+F injuries. It will be used extensively in this paper to assess the relationship between crash variables and crash severity.

Table 1.
Distribution of Occupants, MAIS 3+ and Fatally Injured, Injury Rate, and Front Seat Occupancy Rate for Front Seat Age 12+ Occupants of Vehicles Involved in Rollover Crashes by Vehicle Class.

Front Seat Age 12+	PC	SUV	Van	PU
Occupants	45%	29%	6%	20%
MAIS 3+ F	51%	19%	7%	23%
Injury Rate	7.4	4.3	7.5	7.1
Occupancy Rate	1.25	1.38	1.23	1.18

It is evident from Table 1 that vans constitute a very small percentage of the occupants and injuries in rollovers. Consequently, it is not possible to analyze vans with the same detail and accuracy as the other classes of vehicles. In subsequent analysis, van statistics are included in the totals presented but are not listed separately, due to their small numbers.

Table 1 also lists the front seat occupancy rate for the vehicle classes. The front seat occupancy rate is higher for SUV’s than for passenger cars. The pickup front seat occupancy rate is lower. Occupancy rate equivalency could be achieved by considering only the driver. However, several biases would result. First, front seat occupants may interact with each other during a rollover. Second, the injury risk for the driver may be different from that of the passenger, depending on the directions of roll. Both

front seat occupants were included in the data to follow.

EXPOSURE AND INJURIES BY BELT USE, CRASH TYPE, AND EXTENT OF EJECTION

The distribution of front seat occupants exposed to rollover crashes by belt use and ejection status is shown in Table 2. Approximately 75% of the front seat occupants are belted. Total ejection is a rare occurrence, accounting for 0.2% for the belted population and 4.2% for the unbelted population. However, these rare events account for about 33% of the MAIS 3+F injuries. Injury rates for totally ejected occupants are twelve times higher than for occupants who are non-ejected. The data further shows the effectiveness of restraints in preventing ejection. Serious injuries from total ejection among the belted population are rare, accounting for less than one half of one percent of the seriously injured occupants. Partial ejection accounts for about 9% of the seriously injured occupants. The largest fractions of the seriously injured occupants are: Belted-non-ejected (35.3%), Unbelted-non-ejected (23%) and Unbelted-totally ejected (32.5%). These three categories will be examined separately to determine crash attributes that influence the risk of severe injury.

Table 2.
Distribution of Rollover Exposed Belted and Unbelted Front Seat Age 12+ Occupants, MAIS 3+ and Fatal Injuries, and Injury Rate for Rollover Crashes

Exposure	No-Eject	Total Eject	Part-Eject
Belted	73.6%	0.2%	1.7%
Unbelted	18.7%	4.2%	1.6%
Total	92.3%	4.4%	3.3%
MAIS 3+F	No-Eject	Total Eject	Part-Eject
Belted	35.3%	0.4%	3.9%
Unbelted	23.0%	32.5%	5.0%
Total	58.3%	32.8%	8.9%
Injury Rate	No-Eject	Total Eject	Part-Eject
Belted	3.1	12.7	14.6
Unbelted	7.9	49.6	19.9
Total	4.1	48.0	17.2

Table 3 provides a breakout of the exposure and injury data by belted and unbelted front seat

occupants in for single vehicle rollovers and rollovers after an impact with another vehicle (multi-vehicle).

Multi-vehicle crashes occur in only 19% of the rollovers, but account for 26% of the MAIS 3+ F injured front seat age 12+ occupants. These multi-impact rollovers also have higher injury rates. For multi-impact rollovers, the injury rate is 1.5 times the rate for single vehicle rollovers. For restrained occupants in multi-impact rollovers, the injury rate is 2.0 times higher. These results suggest that severity measures for multi-impact rollovers should include factors in addition to the rollover attributes of the crash.

Another observation from Table 3 is the large difference in injury rates between restrained and unrestrained. The injury rate for the unrestrained is approximately 5 times higher than for the restrained. These results further illustrate the need to examine rollover severity for restrained and unrestrained separately.

Table 3.
Distribution of Rollover Exposed Belted and Unbelted Front Seat Age 12+ Occupants, MAIS 3+ and Fatal Injuries, Injury Rates for Single Vehicle Rollovers, Rollovers in Multi-vehicle Crashes and All Rollover Crashes

Belted	Single	Multi	Total
Exposed	61%	14%	75%
MAIS 3+ F	27%	13%	40%
Injury Rate	2.8	5.8	3.4
Unbelted	Single	Multi	Total
Exposed	20%	5%	25%
MAIS 3+ F	47%	13%	60%
Injury Rate	15.1	18.5	15.7
Combined	Single	Multi	Total
Exposed	81%	19%	100%
MAIS 3+ F	74%	26%	100%
Injury Rate	5.9	8.8	6.4

Tables 4 and 5 show data on populations of unbelted and belted front seat occupants, respectively. The tables provide distributions of non-ejected totally ejected and partially ejected occupants in single and multi-vehicle rollovers.

Table 4 shows data for unbelted occupants. When compared to Single rollovers, Multi-vehicle rollovers almost double the injury rates for the 'No ejection' and 'Partial ejection' categories. The injury risk for

totally ejected occupants is about 50% for both single and multi-vehicle rollovers. This result suggests that in considering factors that influence injury rate, unrestrained totally ejected occupants should be examined as a separate category. It also suggests a separation of multi-vehicle and single rollovers.

Table 4.
Distribution of Unbelted Front Seat Age 12+ Occupants by Ejection Status, MAIS 3+ F Injuries and Injury Rates for Single Vehicle Rollovers, Rollovers in Multi-vehicle Crashes and All Rollovers

No Ejection	Single	Multi	Total
Exposed	60.8%	14.8%	75.6%
MAIS 3+ F	26.5%	11.4%	38.0%
Injury Rate	6.9	12.2	7.9
Partial-Eject	Single	Multi	Total
Exposed	5.5%	1.0%	6.5%
MAIS 3+ F	6.0%	2.2%	8.2%
Injury Rate	17.2	34.4	19.9
Total Ejection	Single	Multi	Total
Exposed	14.7%	2.4%	17.1%
MAIS 3+ F	45.6%	7.9%	53.5%
Injury Rate	49.0	53.0	49.6

Table 5 shows data for belted occupants. The data for totally ejected belted occupants is very sparse, constituting less than 1% of the MAIS 3+ F injuries. The resulting injury rates are unreliable and the total ejection data is not reported in Table 5. Exposure data on partial ejection in multi-vehicle crashes is also sparse for both belted and unbelted occupants. Conclusions based on this data would be unreliable.

Rollovers that occur after multi-vehicle crashes and involve neither ejection nor partial ejection account for 29.2% of the MAIS 3+ F injuries for the belted population and 11.4% for the unbelted. These multi-vehicle crashes increase the injury rate for both belted and unbelted occupants who are non-ejected. For belted occupants the rate is 2.2 times higher than for single vehicle rollovers. For unbelted non-ejected occupants, the rate is 1.8 times higher. These crashes require additional planar crash severity metrics to account for the increased injury rates.

Table 5.
Distribution of Belted Front Seat Age 12+ Occupants by Ejection Status, MAIS 3+ F Injuries, Injury Rates for Single Vehicle Rollovers, Rollovers in Multi-vehicle Crashes and All Rollovers

No Ejection	Single	Multi	Total
Exposed	79.4%	17.8%	97.2%
MAIS 3+ F	59.5%	29.2%	88.7%
Injury Rate	2.5	5.5	3.1
Part-Ejection	Single	Multi	Total
Exposed	1.4%	0.8%	2.3%
MAIS 3+ F	7.3%	2.4%	9.8%
Injury Rate	17.2	10.0	14.6

SEVERITY FACTORS – BELTED, NON-EJECTED OCCUPANTS

The single vehicle rollovers with belted, not-ejected occupants constitute about 60% of the exposed population, but only 23% of the MAIS 3+ Fatal injuries. For the front seat occupants, age 12+ in NASS 1995-2001 this population expands to 1,163,856 occupants of which 29,496 had MAIS 3+ F injuries. This group is considered to be appropriate for detailed examination. Since only a single vehicle is involved, these crashes are less frequently influenced by injury producing pre-rollover events. Consequently, these crashes are more likely to provide insight into how rollover crash variables influence injury severity. One of the most commonly proposed rollover crash severity variables is the number of quarter-turns. This variable is generally related to the energy of the crash. In addition it provides an indication of the duration of exposure of the occupant to the rollover event. However, it does not provide an indication of the severity of the impacts with the ground or the consequence of the resulting vehicle intrusion.

The figures to follow examine the occupant exposure and resulting MAIS 3+F injured non-ejected front seat occupants by number of quarter-turns. The number of quarter-turns was coded 1 to 16 and 16+. End-over-end rollovers were excluded from these charts and were analyzed separately. The vertical lines show the quarter-turns during which the first, second, and third roof contacts occur.

For the belted occupants, the MAIS 3+ F injured lags the occupant exposure at low numbers of quarter-

turns. This lag occurs for all three vehicle types. However, it is most pronounced in the passenger cars. As shown in Figure 2, belted front seat occupants in passenger cars display a large increase in serious injuries after the second roof impact. This trend suggests that the number of roof impacts may be an appropriate rollover severity indicator for the belted not-ejected population.

Figure 3 shows the distribution of MAIS 3+ F injured occupants who were belted, non-ejected and were exposed to single vehicle rollovers. Figure 4 shows the injury rate for this MAIS 3+ F population per 100 belted front seat occupants exposed to single vehicle rollovers. A breakout of the distribution of injuries and injury rates for different vehicle classes is shown in Tables 6 and 7. The data is presented in terms of number of roof impacts. Zero roof impacts corresponds to one quarter-turn. One roof impact corresponds to 2 through 5 quarter-turns. Two impacts corresponds to 6 through 10 quarter-turns. Eleven or more quarter-turns are designated as 3+ roof impacts.

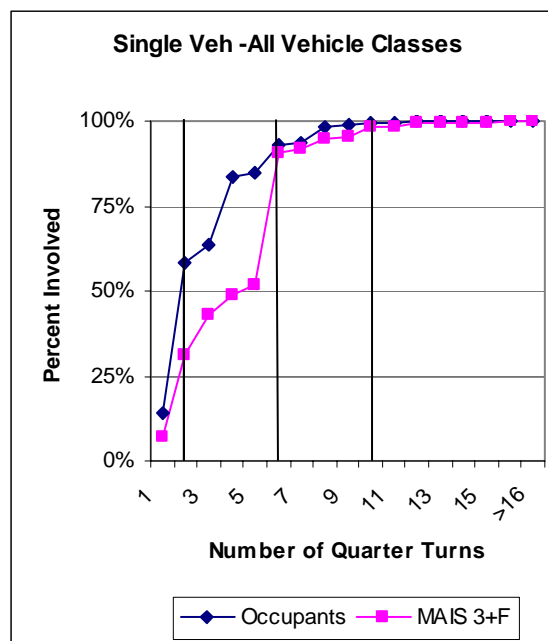


Figure 1. Number of Quarter-turns in Single Vehicle Rollovers for Non-Ejected Front Seat Belted Occupants Ages 12+ and Non-Ejected Front Seat Belted Occupants Ages 12+ with MAIS 3+F Injuries

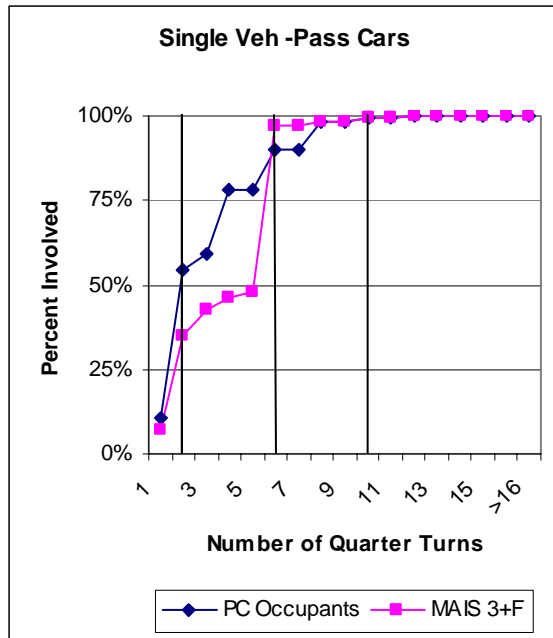


Figure 2. Number of Quarter-turns in Single Vehicle Passenger Car Rollovers for Non-Ejected Front Seat Age 12+ Belted Occupants and Non-Ejected Front Seat Belted Age 12+ Occupants with MAIS 3+F Injuries

Table 6.
Distribution of Belted Non-Ejected Age 12+ Front Seat Occupants with MAIS 3+ F Injuries in Single Vehicle Rollovers

Nr Roof Impacts	PC	SUV	PU	Total
0	7%	6%	6%	7%
1	41%	61%	56%	45%
2	50%	21%	32%	43%
3+	2%	12%	6%	5%

Table 7.
Injury Rate per 100 Exposed for Belted Non-Ejected Front Seat Age 12+ Occupants with MAIS 3+ F Injuries in Single Vehicle Rollovers

Nr Roof Impacts	PC	SUV	PU	Total
0	2.7	0.6	0.2	1.2
1	2.4	0.7	0.9	1.5
2	10.3	2.2	3.5	7.5
3+	3.2	20.9	7.3	9.3
All	4.1	0.9	1.0	2.5

Table 7 and Figure 4 show that for this population, the injury rates generally increase with number of roof impacts. The increase is particularly large when the number of roof impacts exceeds one. More than half of the injured population in passenger cars is exposed more than one roof impact. Overall, about 48% of this injured population is exposed to the higher injury rate environment associated with more than one roof impact.

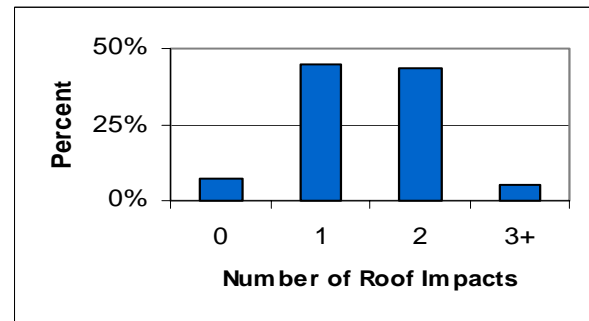


Figure 3. Distribution of Belted Non-Ejected Front Seat Age 12+ Occupants with MAIS 3+ F Injuries in Single Vehicle Rollovers by Number of Roof Impacts

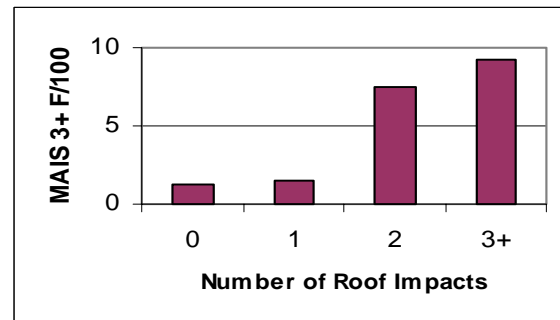


Figure 4. Injury Rate per 100 Exposed for Belted Non-Ejected Front Seat Age 12+ Occupants with MAIS 3+ F Injuries in Single Vehicle Rollovers by Number of Roof Impacts

The injury rate distribution shown in Figure 4 suggests that number of roof impacts may be an appropriate injury severity indicator for this population. A partition of one roof impact and more than one roof impact is a suggested injury severity indicator for this population of rollovers.

SEVERITY FACTORS—UNBELTED, NON-EJECTED OCCUPANTS

The single vehicle rollovers with unbelted, not-ejected occupants contribute about 16% of the MAIS 3+ F injured age 12+ front seat occupants in rollovers. The size of this population in the database

was 290,700 occupants with 20,027 MAIS 3+ F injuries. The distribution of the injured population with number of quarter-turns is shown in Figure 5. The figure shows that the injured occupants follow closely the exposed occupants. An influence of roof contacts on injury rate is not evident from this Figure.

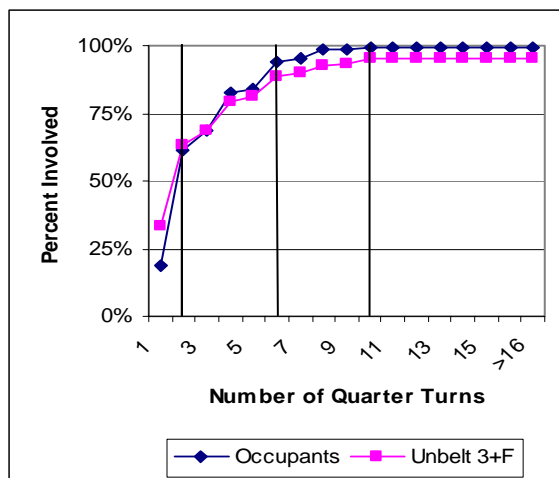


Figure 5. Number of Quarter-turns in Single Vehicle Rollovers for Unbelted Front Seat Age 12+ Occupants and Non-Ejected Unbelted Front Seat Age 12+ Occupants with MAIS 3+F Injuries

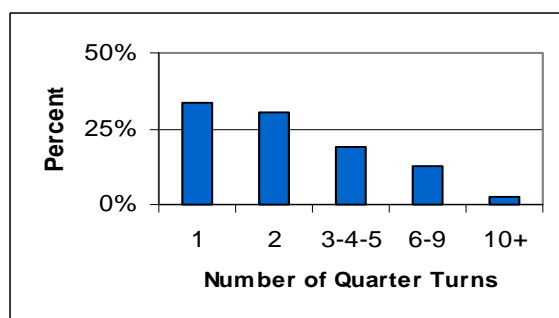


Figure 6. Distribution of Unbelted Front Seat Age 12+ Occupants with MAIS 3+ F Injuries in Single Vehicle Rollovers by Number of Quarter-turns

Figure 6 shows the distribution of MAIS 3+ F injured occupants who were unbelted and were exposed to single vehicle rollovers. Figure 4 shows the injury rate for this MAIS 3+ F population per 100 unbelted front seat occupants exposed to single vehicle rollovers.

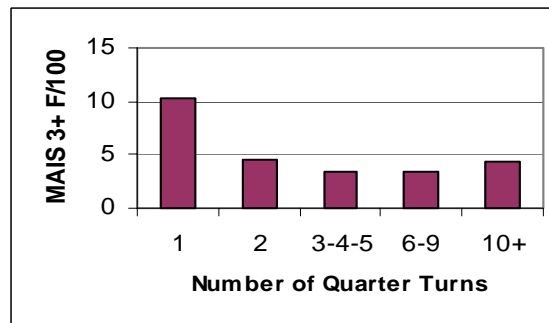


Figure 7. Injury Rate of Unbelted Non-Ejected Front Seat Age 12+ Occupants with MAIS 3+ F Injuries in Single Vehicle Rollovers by Number of Quarter-turns

The Figures show that the largest fraction of injured occupants and the highest injury rate is for the one quarter-turn category. The crash severity of the one quarter-turn category is increased by a large fraction of impacts with fixed objects before or after the rollover occurs. A detailed examination the NASS case files disclosed that there were 29 non-ejected unrestrained front seat occupants age 12+ in single vehicle rollovers that involved only one quarter-turn. When weighting factors were applied this population expanded to 4,792. Of this population 28% received their injuries from impacts with fixed objects prior to the rollover. Another 66% received their injury from impacts with fixed objects other than the ground during or after the rollover. These impacts were commonly trees or poles that impacted the roof and restrict the rollover motion, resulting in a more severe impact that would occur in a pure rollover. If these two conditions were removed, the injury rate for one quarter-turn would be less than one per 100 exposed.

These conditions that aggravate the rollover severity are most apparent in the one-quarter-turn category, but are present in other rollover categories as well. Both of these conditions need to include planar crash severity metrics, such as delta-V, in determining the rollover crash severity. Added data elements in NASS to easily identify cases with planar impacts that increase the injury risk in rollovers would be desirable.

Another observation from Figure 7 is that for the unrestrained, non-ejected population, the injury rate is relatively constant for more than two quarter-turns. Unbelted occupants that are non-ejected and are not injured on the initial impact have relatively low serious injury rates in single vehicle rollovers. This result indicates the value of occupant containment during the rollover.

SEVERITY FACTORS - UNBELTED, EJECTED OCCUPANTS

Total ejection of an occupant is an undesirable intermediate outcome of a rollover. Risk of death and severe injury is unacceptably high for occupant ejections. Once ejection occurs, the existing safety features are defeated and serious injury is a high probability, but almost random consequence. Because of the undesirability of ejection, the analysis to follow includes all ejections, not only those with MAIS 3+ F injuries.

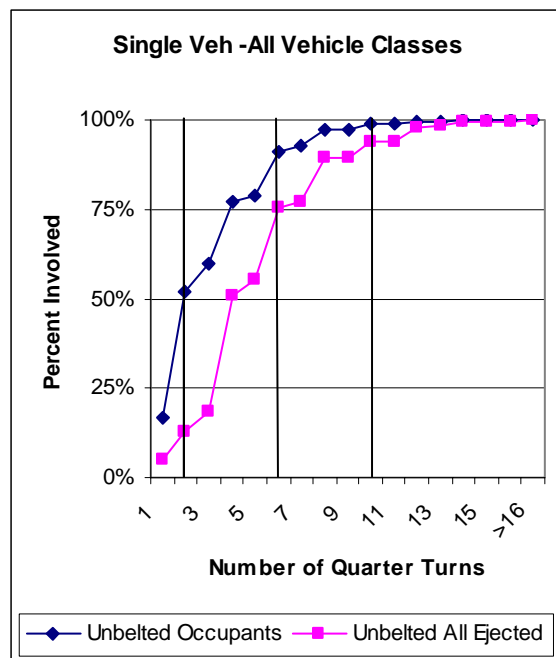


Figure 8. Number of Quarter-turns in Single Vehicle Rollovers for Unbelted Front Seat Age 12+ Occupants and Ejected Unbelted Front Seat Age 12+ Occupants

Figure 9 shows the ejection rate for unbelted age 12+ front seat occupants in single vehicle rollovers by number of quarter-turns. The population of unbelted occupants exposed to single vehicle rollovers was 391,562. Figure 10 shows the same information as a function of roof impacts. Table 8 shows a breakout of the percentage of the ejected population by number of quarter-turns for various vehicle classes.

Figure 9 shows that the ejection rate uniformly increases with number of roof impacts. The breakout by number of quarter-turns shown in Figure 10 indicates that the ejection risk for 4 through 9 quarter-turns is about the same. Table 8 shows that about 33% of the ejections occur at 4 quarter-turns

(one roof impact) and about 34% occur at 6-9 quarter-turns (two roof impacts). This result suggests that the 4 quarter-turn rollover which produces the largest fraction of ejections in pickups and SUV's has about the same ejection rate as rollovers with two roof contacts. Consequently, the four quarter-turn single vehicle rollover stands out as being equivalent in ejection potential to a two roof impact rollover.

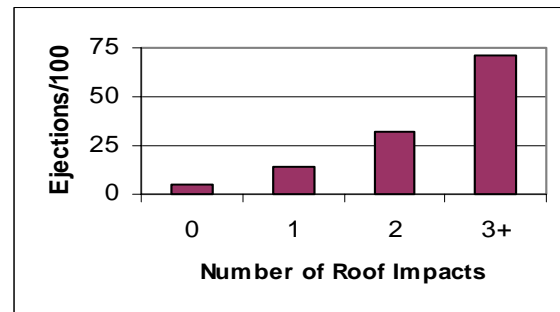


Figure 9. Ejection Rate of Unbelted Ejected Front Seat Age 12+ Occupants in Single Vehicle Rollovers by Number of Quarter-turns

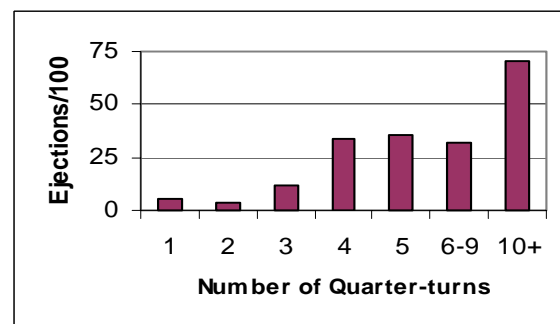


Figure 10. Ejection Rate of Unbelted Ejected Front Seat Age 12+ Occupants in Single Vehicle Rollovers by Number of Quarter-turns

Table 8. Distribution of Unbelted Ejected Front Seat Age 12+ Occupants in Single Vehicle Rollovers by Number of Quarter-turns

Nr Quarter-turns	PC	SUV	PU	Total
1	2%	14%	1%	5%
2	11%	8%	4%	8%
3	8%	5%	1%	5%
4	25%	32%	43%	33%
5	2%	2%	7%	4%
6-9	37%	32%	34%	34%
10+	14%	7%	9%	10%

For ejected occupants in single vehicle rollovers, the ejection rate generally increases with the number of quarter-turns. Quarter-turns in the 4 to 9 range have an ejection rate five times that of crashes with less than 4 quarter-turns. The ejection rate doubles again for quarter-turns greater than nine. The results validate the continued use of the number of quarter-turns as an appropriate metric for ejection rate. However, number of roof impacts provides a more uniform relationship between crash severity and ejection rate. Each additional roof contact increases the ejection rate by a factor of about 2.3.

COMPARISON WITH OTHER STUDIES

In this study, overall belt use in rollovers was found to be around 75%. This belt use is higher than the 50% reported by Malliaris [Malliaris 1999]. However, Malliaris discounted the belt use records by 20% due to over reporting in NASS CDS. Accuracy of belt use is an important factor for studies dealing with effectiveness of countermeasures. The present study does not deal with effectiveness, so no belt use discounting was introduced.

State Data System Records, based on Police Accident Reports, report 73 percent restraint use over the period 1995 through 1999 [HS 809 301, 2002]. This is consistent with the belt use observations reported by NOPUS [NHTSA, June 2001 Mini NOPUS.]

In this study, the belt use for seriously or fatally injured occupants was found to be only about 40%. For FARS 2000, the belt use in fatal rollover crash occupants who died in rollovers was 28%. [Deutermann 2002]

Malliaris found the injury risk of MAIS 3+ F injuries in rollovers was 2.1 for belted occupants [Malliaris, 1999]. This is consistent with the rate found in this paper. Partyka's 1978 work with The National Crash Severity Study indicated approximately 16 MAIS three or greater injuries per 100 occupants exposed to rollover [Partyka 1978]. This estimate was for belts as used and it included both belted and unbelted occupants. An update, using the injury codification inherent to NASS – CDS for the years 1995 to 1999 indicated six MAIS three or greater injuries per 100 occupants exposed to rollover, as reported in the DOT Docket No. NHTSA-1999-5572; Notice 2.

Even at a relatively high overall reported belt usage, the number of seriously and fatally injured occupants who are unrestrained remains extremely high.

CONCLUSIONS

For belted occupants and unbelted ejected occupants in single vehicle crashes, the number of roof impacts is an appropriate severity indicator. For ejected occupants, the ejection risk generally increases with the number of quarter-turns. However, number of roof impacts provides a more uniform relationship between crash severity and injury risk. For each added roof impact up to 3 the injury rate increases by a factor of about 2.3.

For non-ejected unbelted occupants in single vehicle crashes, the most frequent and most injurious category is one quarter-turn of roll. An examination of injuries in cases with one quarter-turn indicates that impacts with fixed objects other than the ground during the rollover increase the risk of the injuries. At one quarter-turn, the roof is vulnerable to impact with trees or poles that may abruptly stop the progress of the rollover and increase the risk of injury.

For crashes that involve another vehicle prior to rollover, the injury risks are about 1.5 times higher than for single vehicle rollovers. For non-ejected belted occupants, the increased risk for multi-vehicle involvement is about 2.2. Impacts with a fixed object such as a tree or wall prior to rollover also carry higher risks. Consequently, additional severity measures such as the delta-V for the pre-rollover crash event are required. Additional data elements to quantify the severity of these impacts would greatly assist in the analysis of rollovers.

Risks of severe or fatal injuries in rollovers may be increased by collisions with fixed vertical objects such as trees and walls during the process of the rollover. In such cases, the collision can induce a more hazardous environment than would have occurred if the rollover had not been impeded. Additional data elements may be required to identify these cases and provide added predictors for the crash severity measurement.

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